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A NOTE ON RING AND POLYGONAL FRACTURES IN TWO LUNAR CRATERS, AND THEIR SIGNIFICANCE FOR TERRESTRIAL MAGMA EMPLACEMENT

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Abstract: Two volcanic craters on the far side of the moon exhibit ring and polygonal fractures which exemplify the notion of ring-shaped "fracture zones" put forward by Marland P. Billings in 1943 as an emplacement mechanism for steep or vertical ring dykes. On Earth, magma irruption usually obliterates evidence of its emplacement mechanism; the lunar craters were never engulfed by magma after the fractures formed, and display the postulated patterns of ring and block fracturing "frozen in the act" for 4 billion years.

In 1966, I published an account of an igneous ring complex at Cobaw in central Victoria, comprising a thick, steeply-dipping, granite ring dyke surrounding several younger intrusions (Stewart 1966). The granite ring virtually obliterated the evidence of its mechanism of emplacement, and I used the notion put forward by Billings (1943) of large-scale piecemeal stoping of a ring-shaped "fracture zone" to emplace the granite, followed by large-scale fracturing of the central block of country rock to emplace the next (and largest) intrusion. But, do ring fracture zones really exist? In the same year, the Lunar Orbiter 1 spacecraft of the United States National Aeronautics and Space Administration photographed a group of internally-rilled or floor-fractured craters (Fig. 1A) which display the very fracture patterns postulated at Cobaw, but which appear not to have been engulfed by magma. In 1972, the crew of the Apollo 17 manned space flight mission included the craters in their stereoscopic photo-coverage of the Moon (Fig. 2A, B). McCauley (in Cortwright 1968), Kosofsky and Farouk El-Baz (1970), and Short (1975) depicted and commented briefly on the craters, and Schultz (1976a, b) discussed the southernmost crater in some detail.

GEOLOGY

The craters in question are situated on the far side of the moon at latitude 4°30'S, longitude 145°48'E. The craters are in densely-cratered highland terrain, and are therefore older than 4 b.y. (Taylor 1975). There are four adjoining craters, with overall dimensions of 77 km by 40 km (Fig. 1A, B) for the group.

Crater Descriptions

Crater 1, here called oval crater, is about 40 km long, and elliptical; it approximates a Class III (wide floor moat) crater in the classification of Schultz (1976b), but lacks polygonal fractures common in the class. The floor has a hummocky surface, and is at about the same level as the surrounding terrain outside the rimcrest. The floor is slightly raised in the southwest, forming a platform tilted gently to the northeast (Fig. 2A). Near the rimwall (Fig. 1A, B) the floor is cut by several concentric arcuate fractures with V-shaped profiles. The main fracture extends for 320° around the floor, and defines the inner edge of the moat. In the southwest, this fracture appears to be a normal fault in, and may therefore be considerably younger than, the hummocky floor surface (Fig. 2A, B). An arcuate patch of dark material is situated outside and next to the main fracture at this locality, and others are situated on the main fracture in the south and north of the crater. Similar dark patches but irregular in outline and each surrounding a small dark crater are located 3 km inside the main fracture in the southwest and northwest of the crater floor, and also where oval crater meets crater 2 (see below). These three are probably dark-halo pyroclastic deposits surrounding cinder cones (Salisbury *et al.* 1968), and the three arcuate patches may also be pyroclastic deposits derived from the main ring fracture.

Crater 2, or turtle crater, is about 30 km long, polygonal, and is a Class IVa (narrow floor moat) crater in Schultz's classification. The floor and rimwall meet at a pronounced V-angle, forming the narrow moat. The floor is lower than the floor of oval crater, and also lower than the terrain outside the rimcrest (Fig. 2A, B). The floor of turtle crater is cut by numerous straight or arcuate fractures with V-shaped profiles, forming a polygonal pattern of plates resembling a turtle's shell. The fractures are considerably wider and deeper than those of oval crater. A discontinuous ring fracture similar to that in oval crater is present in the floor near the rimwall (Fig. 1A, B), and is shallower than the straight or arcuate fractures that cross the floor. The plates are tilted outward from a high point in the northwest of the floor (Fig. 2A, B), indicating that the crater floor is domed, as noted by McCauley (in Cortwright 1968) and by Schultz (1976a). The easternmost plates (adjoining the eastern rimwall) are higher than their neighbours to the west (Fig. 2A, B), indicating normal faulting (Fig. 1B).

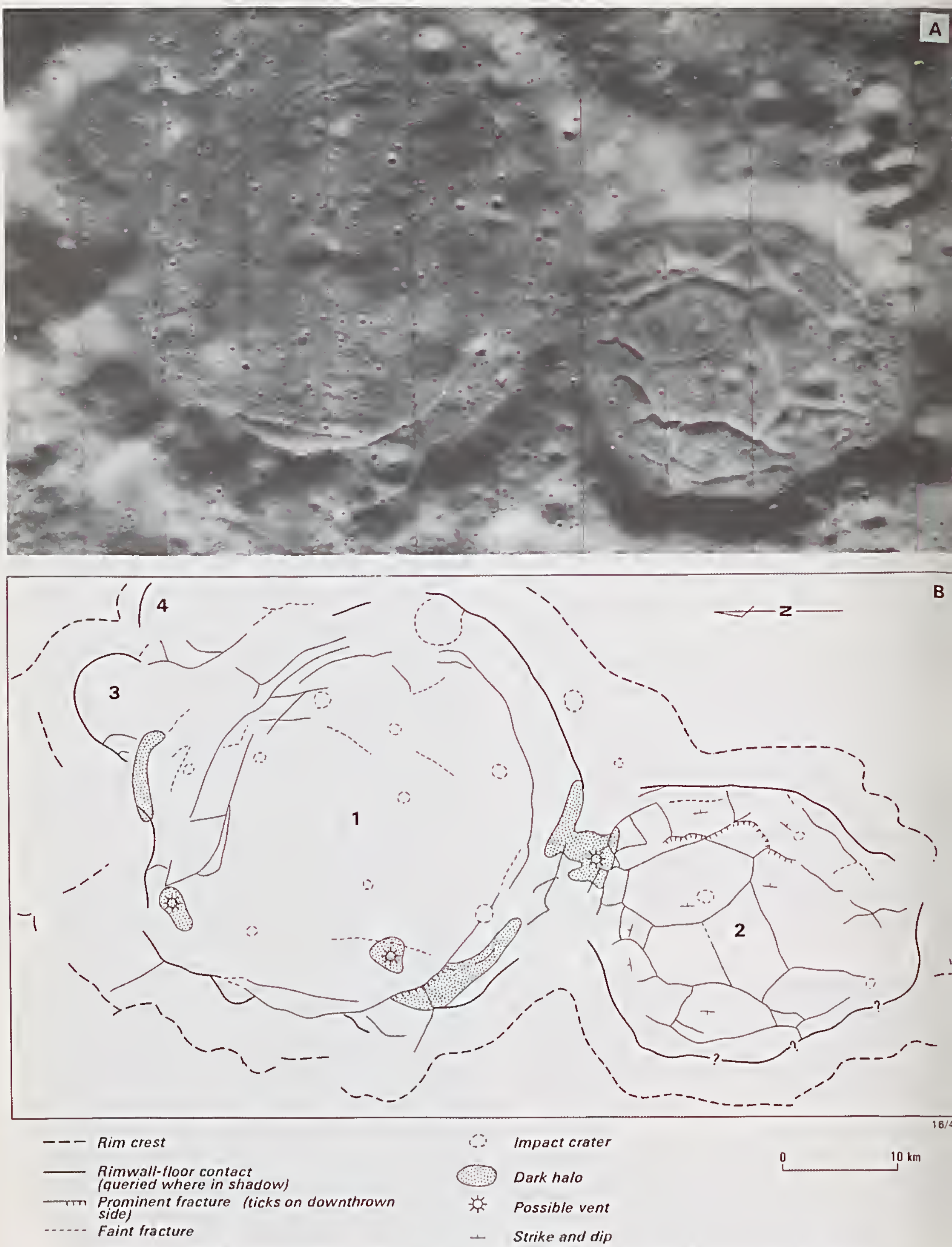


Fig. 1—A, High-resolution photograph by United States NASA Lunar Orbiter 1 spacecraft on 24 August 1966, showing floor-fractured craters at longitude 145°48′E, latitude 4°30′S, on far side of moon. NASA photograph L-66-7954, frame 115 published by permission of the Principal Investigator, Mr L. J. Kosofsky, and the National Space Science Data Center through the World Data Center-A for Rockets and Satellites, Maryland, U.S.A. B, Structural map showing major fractures traced from Fig. 1A, and dark haloes with possible vents, dip attitudes and faults plotted from Fig. 2.

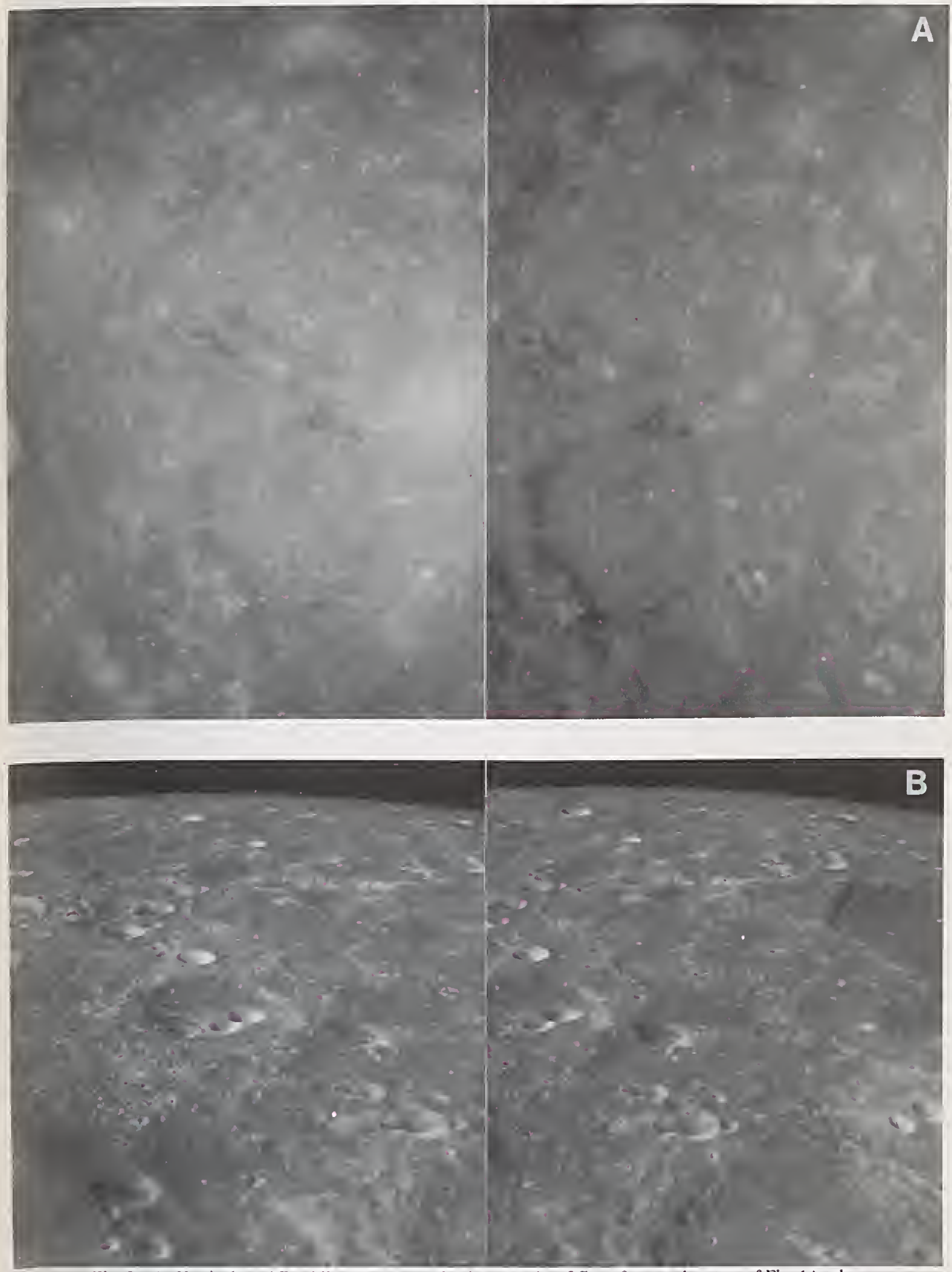


Fig. 2—A, Vertical, and B, oblique stereoscopic photographs of floor-fractured craters of Fig. 1A taken by United States NASA Apollo 17 manned space-flight mission in 1972. NASA photographs AS17-215 and 216 (vertical) and AS17—855 and 856 (oblique) published by permission of the Principal Investigator, Dr Frederick J. Doyle, and the National Space Science Data Center through the World Data Center-A for Rockets and Satellites, Maryland, U.S.A.

Two smaller craters (Fig. 1B, nos. 3, 4), each about 8 km across, are situated to the northeast of oval crater. Their floors are hummocky and horizontal, and bounded by annular valleys with a V-shaped profile. The floor of crater 4 is higher than that of crater 3 (Fig. 2A, B).

A discontinuous rim surrounds the craters, and forms a ridge southeast of oval crater and east and west of turtle crater, and a chain of irregular hills elsewhere (Fig. 2A, B). The outer limit of the rimflank is poorly defined, and to the southwest, northeast, and southeast the hills extend well away from the crater and merge into the general terrain of the region, giving the craters the appearance of down-dropped areas in hilly country. There is no rim where the craters join.

AGE

Apart from the fractures, the floors of the four craters have the same appearance and undulating or hummocky surface as the surrounding lunar terrain. Their diffuse, degraded, or subdued appearance corresponds to an age index of about 2.5 in the relative age sequence of Pohn and Offield (1969) for craters 16 to 48 km in diameter (Class 2), giving a chronological age of about 4.4 b.y. (Short 1975).

DISCUSSION

IMPACT OR VOLCANIC ORIGIN?

Short (1975, p. 115) and the Basaltic Volcanism Study Project (1981) list morphological features diagnostic of impact and volcanic craters on the moon. The craters described here have the following features indicative of volcanic origin:

—absence of central peaks and of interior terraces at the rimwall;

—floors which have discontinuous contacts with the rimwall and which extend into the smaller craters to the northeast, both features being suggestive of lava fill (Schultz 1976b);

—non-circular plans;

—peripheral constructs (craters 3 and 4) implying flank eruptions;

—contiguous occurrence as a group.

Additional evidence for volcanic origin includes:

—the horizontal floors of craters 3 and 4. These craters are too small to have undergone isostatic rebound after impact (Lowman 1969, fig. 53), indicating that the floors are volcanic fill:

—the different levels of the floors of the four craters;

—the non-parallelism of the long axes of oval and turtle craters, negating the possibility of impact by two bolides travelling together. Alternatively, impact by two bolides of different age and trajectory is negated by the similar appearance and hence similar age of the two crater floors and by the absence of any overlapping or superimposed rim where the two craters touch, indicating simultaneity of crater formation.

Hence, all the evidence indicates a volcanic origin for the craters, and is opposed both to impact and to impact followed by volcanism.

ORIGIN OF FRACTURES

Short (1975) attributed the polygonal fractures in turtle crater to shrinkage cracking of rapidly-cooled lava, but the many lunar craters containing cooled lava that shows no fractures disproves this possibility (Schultz 1976b), and the doming of the crater floor indicates expansion instead.

The ring fractures prominent in oval crater indicate either elevation or subsidence of the crater floor as happens in terrestrial craters in response to magmatic inflow or withdrawal. The tilting of the floor platform of oval crater is consistent with subfloor sill intrusion, and the doming of the floor of turtle crater is consistent with intrusion of a subfloor laccolith, batholith, or diapir. The ring fractures may mark the boundaries of the subfloor intrusions. A small amount of magma erupted through the fractures and formed the patches of dark halo (pyroclastic?) material at and near the main ring fracture of oval crater. The two small craters (Fig. 1B, nos. 3, 4) have no surface fractures, but have a prominent V-shaped moat between floor and rimwall (Fig. 2A, B). Schultz (1976b) suggested that this type of moat arises either by small differential floor movement, or represents the terminus of the lava flow(s), which typically range from 10 to 50 m in thickness on the moon, forming the crater floor. The difference in level of the floors of craters 3 and 4 indicate differential floor movement.

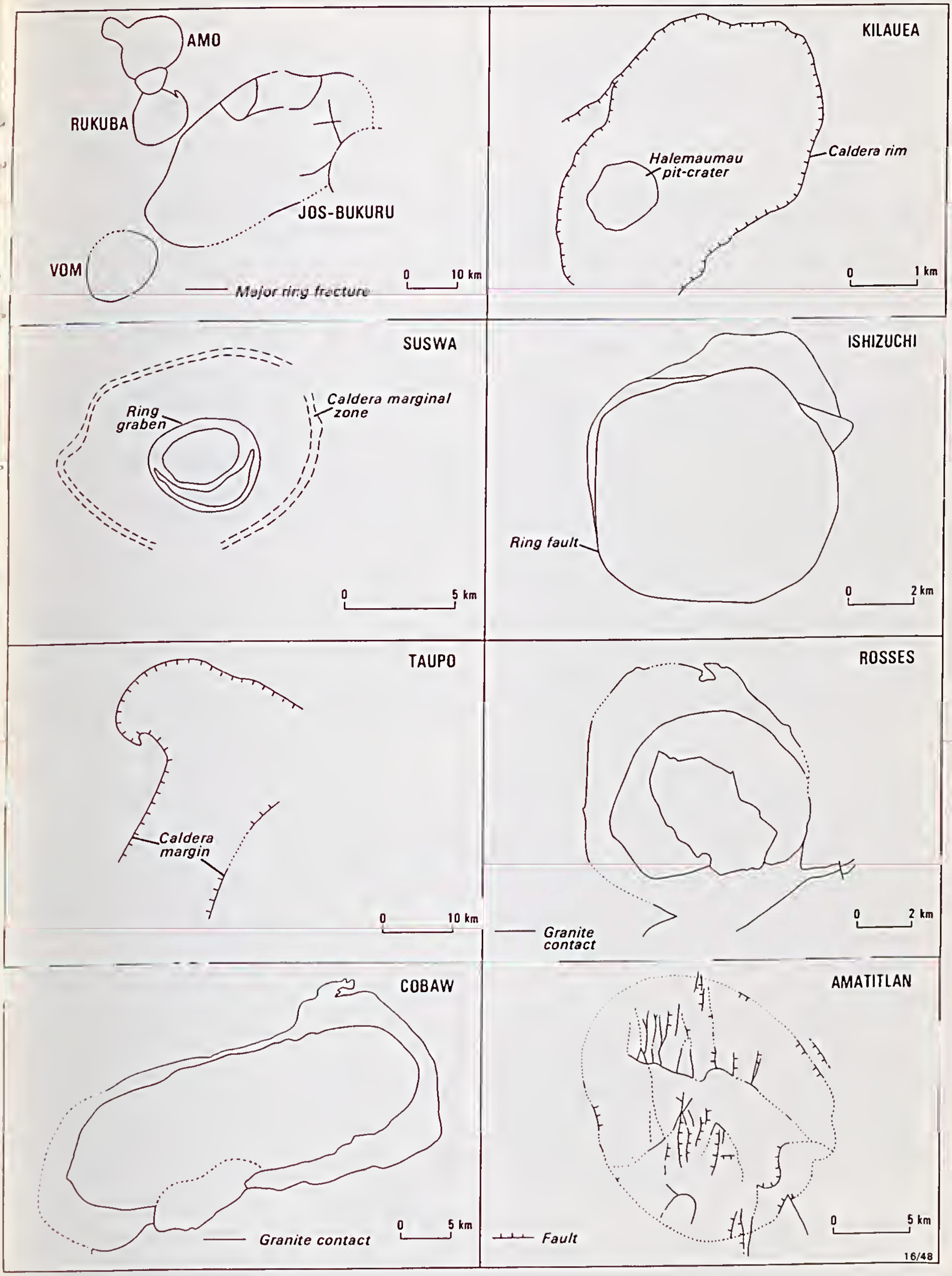
Schultz (1976b) proposed the following sequence of events for endogenic Class IVa craters:

1. Establishment of craters by caldera collapse into a magma chamber;
2. Intrusion of magma (resurgence) into the region below the collapsed caldera blocks, and eruption of magma through the fractures between and around the blocks to form the floor unit (lava and/or tephra), with a narrow moat at the edge representing flow termini or the site of differential floor movement.

At turtle crater, these events were followed by further inflow of subsurface magma, causing doming and polygonal fracturing of the floor of turtle crater, followed by subsidence centred in the northwest, leaving the easternmost plates as upstanding cuestas.

Oval crater, although it has the wide moat of a Class III crater, lacks the polygonal floor fractures and central peaks of Class III, and appears to be simply

Fig. 3—Structural sketch maps of Amo-Rukuba and Jos-Bukuru ring complexes of Nigeria (after Jacobson *et al.* 1958), Halemaumau crater, Hawaii (after Holmes 1965), Suswa volcano, Kenya (after Johnson 1969), Ishizuchi cauldron, Japan (after Yoshida 1984), Taupo caldera volcano, New Zealand (after Wilson *et al.* 1984), Rosses granitic ring-complex, Ireland (after Pitcher 1953), Cobaw Granite, Victoria (after Stewart 1966), and Amatitlan caldera, Guatemala (after Wunderman & Rose 1984). Faults dashed where approximate, dotted where inferred; ticks on downthrown side.


AMO
RUKUBA
JOS-BUKURU
VOM
0 10 km
Major ring fracture
KILAUEA
Halemaumau pit-crater
Caldera rim
0 1 km
SUSWA
Ring graben
Caldera marginal zone
0 5 km
ISHIZUCHI
Ring fault
0 2 km
TAUPO
Caldera margin
0 10 km
ROSSES
0 2 km
Granite contact
COBAW
0 5 km
Granite contact
AMATITLAN
0 5 km
Fault
16/48

a crater that reached stage 2 of the Class IVa sequence above, but instead of then doming underwent ring fracturing and tilting of the entire floor platform above an intruding sill, forming the wide moat in the west and south of the crater, accompanied by small pyroclastic eruptions at and near the ring fracture.

SIGNIFICANCE OF FRACTURE PATTERNS

The resemblance of the group of lunar craters described here to some terrestrial ring complexes is striking, and in general outline the lunar group could be a sibling of the Amo-Rukuba ring complex of Nigeria (Jacobson, MacLeod & Black 1958) (Fig. 3). Numerous recent volcanic craters on Earth show ring and block fractures, and thereby support a volcanic origin for the lunar craters. Terrestrial examples which show ring fractures include Halemaumau in Kilauca caldera, Hawaii (Holmes 1965), Suswa in Kenya (Johnson 1969), and Ishizuchi in Japan (Yoshida 1984) (Fig. 3). Maars are another example of ring fracturing of volcanic origin (Ollier 1967). Block fracturing in volcanic centres is exemplified by the Taupo caldera in New Zealand (Wilson *et al.* 1984) (Fig. 3). Plutonic complexes which show ring and block fracturing include Jos-Bukuru in Nigeria (Jacobson *et al.* 1958), the Rosses, Ireland (Pitcher 1953), and Cobaw, Victoria (Stewart 1966) (Fig. 3). Turtle crater itself resembles the active Amatitlan caldera in Guatemala (Wunderman & Rose 1984) (Fig. 3), which comprises a network of faults separating polygonal blocks of volcanics 1 to 5 km across inside a ring fault. Oval crater exhibits a nearly complete ring fracture, and in the north and west appears to exemplify Billings' (1943) notion of a ring-shaped zone of intersecting fractures surrounding a central mass of country rock.

On Earth, the ring fracture zone model provides a mechanism for magma to stope its way up through the crust, forming a steep or vertical ring dyke; this is followed by subaerial [e.g. Glen Coe, Scotland (Clough *et al.* 1909); Valles, New Mexico (Smith *et al.* 1961); Ishizuchi, Suswa, Jos-Bukuru] or subsurface (Rosses, Cobaw) cauldron collapse of the central block. This collapse takes place either as a single mass or as several smaller masses. Oval crater exhibits the ring fractures necessary for the former to occur, and turtle crater the block fractures for the latter.

CONCLUSION

The lunar craters described here support two hypothetical notions of terrestrial magma emplacement at a high level in the crust: the ring fracture zone of Billings (1943), and large-scale block fracturing. Lava never obliterated the lunar fractures, enabling the craters to preserve the evidence of the magma emplacement mechanism, evidence which is usually obliterated on Earth by the magma itself.

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